Microwave Argon plasma torch

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Argon plasma torch at atmospheric pressure sustained by travelling electromagnetic surface wave is theoretically studied by means of self-consistent model. The model is based on self-consistently linked kinetic and electrodynamic sets of equations describing both the gas discharge properties and the wave propagation characteristics along the axially inhomogeneous Argon plasma column surrounded by vacuum. A steady-state Boltzmann equation coupled with a collisional–radiative model for Argon discharge is numerically solved together with Maxwell's equations for an azimuthally symmetric TM surface wave. The Argon ground state and seven excited states (4s, 4p, 3d, 5s, 5p, 4d, 6s) considered as blocks of levels are taken into account. The axial distributions of wave and plasma characteristics as well as a 3D plot of electron energy distribution function (EEDF) are obtained.

1. Inroduction

An efficient way of creating pure (electrodeless) plasmas in a wide range of operating conditions is by electromagnetic wave traveling along a dielectric boundary. The mechanism of plasma creating is the following: The wave electric field heats the electrons and they expend the obtained energy for ionization and excitation of the neutral atoms creating and sustaining in this way the discharge. In the same time the plasma becomes a part of the waveguide structure for the wave propagation. The electrons absorb the wave energy thus it decreases along the plasma column. The plasma density decreases too and the plasma column is axially inhomogeneous. This mechanism of creating and sustaining the plasma requires self-consistent model describing the kinetics of electrons and heavy particles in the discharge and the electrodynamics of wave propagation along the sustained plasma in the same time [1].

2. Self-consistent model

The self-consistent model is based on a steady-state Boltzmann equation coupled with a collisional–radiative model for Argon discharge and numerically solved together with Maxwell's equations for an azimuthally symmetric TM surface wave [2].

Depending on the discharge conditions (gas nature and gas pressure) it is of great importance to choose appropriate energy levels diagram and corresponding elementary processes. In our model for atmospheric pressure plasma the Argon ground state and seven excited states (4s, 4p, 3d, 5s, 5p, 4d, 6s) considered as blocks of levels are taken into account (Fig. 1). Three types of elementary processes are taken into account: Processes of charged particles creation (direct, stepwise, Penning and associative ionization, and conversion to molecular ions); loss of charged particles (dissociative and three body recombination, and diffusion); energy exchange processes (elastic scattering, excitation and de-excitation by electron impact, and radiative transitions, Fig. 1).

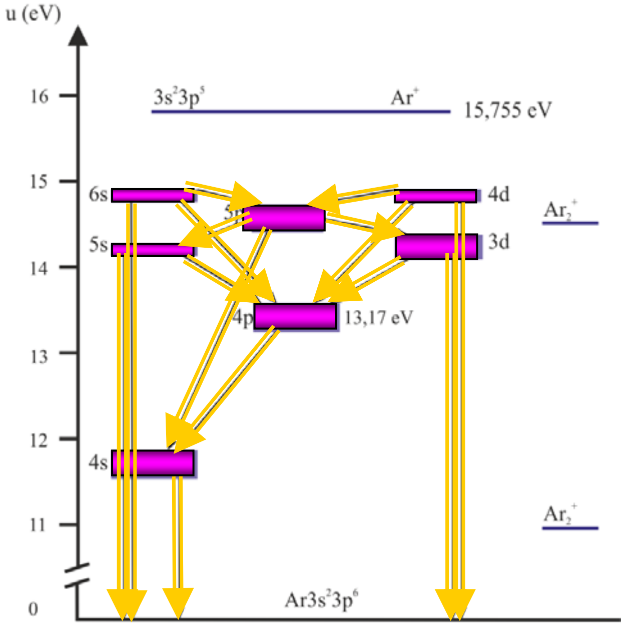

Fig. 1. Argon energy levels' diagram and radiative transitions

The EEDF is obtained by solving the electron Boltzmann equation using two-term expansion in Legendre polynomials. The two-term expansion gives sufficient accuracy in obtaining the discharge properties in noble gases. In argon plasmas the

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14. ABSTRACT **Argon plasma torch at atmospheric pressure sustained by travelling electromagnetic surface wave is theoretically studied by means of self-consistent model. The model is based on self-consistently linked kinetic and electrodynamic sets of equations describing both the gas discharge properties and the wave propagation characteristics along the axially inhomogeneous Argon plasma column surrounded by vacuum. A steady-state Boltzmann equation coupled with a collisionalradiative model for Argon discharge is numerically solved together with Maxwells equations for an azimuthally symmetric TM surface wave. The Argon ground state and seven excited states (4s, 4p, 3d, 5s, 5p, 4d, 6s) considered as blocks of levels are taken into account. The axial distributions of wave and plasma characteristics as well as a 3D plot of electron energy distribution function (EEDF) are obtained.**						
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EEDF usually strongly differs from Maxwellian and chages along the plasma column (this is illustrated in Fig. 2). For the theoretical treatment of microwave discharges sustained by travelling wave it is of major importance to determine the EEDF precisely in order to obtain correct values at each axial position of the electron transport parameters, the rates of elementary processes, and other key quantities as the effective electron-neutral collision frequency for momentum transfer ν_{eff} and the mean power θ required for sustaining an electron-ion pair in the discharge.

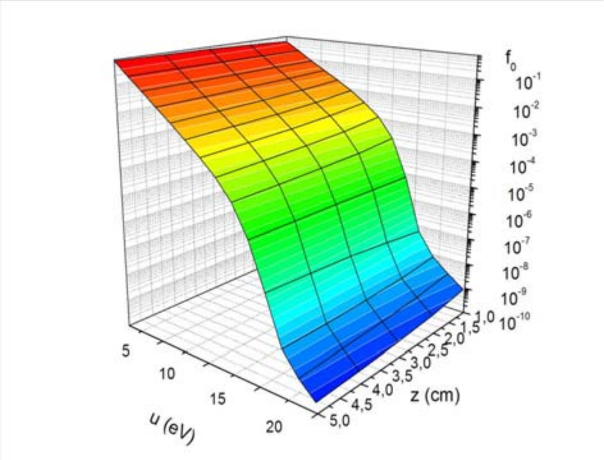

Fig. 2. EEDF is non-Maxwellian and changes along the plasma column

The electron–neutral collision frequency for momentum transfer ν_{eff} turned out to be important parameter not only in the plasma kinetics. At atmospheric pressure the effect of collision frequency appears in the plasma permittivity ε_{p}. The high-frequency plasma permittivity ε_p is derived from the simplest model of cold collisional electron plasma [3] and can be presented in the form:

$$\varepsilon_{\mathrm{p}} = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega(\omega + i\nu_{\mathrm{eff}})} = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2}\left(1 + \frac{\nu_{\mathrm{eff}}^2}{\omega^2}\right)^{-1} + i\frac{\nu_{\mathrm{eff}}}{\omega}\frac{\omega_{\mathrm{p}}^2}{\omega^2}\left(1 + \frac{\nu_{\mathrm{eff}}^2}{\omega^2}\right)^{-1} \quad (1)$$

where $\omega_{\mathrm{p}} = \sqrt{4\pi e^2 n / m}$ is the electron plasma angular frequency, ω is the wave angular frequency, n is the plasma density and the other notations are standard. Since the expression (1) is complex the wave number is also complex, $k = k_{\mathrm{r}} + ik_{\mathrm{i}}$. The real part of the wave number k_{r} is the propagation coefficient and the imaginary part k_{i} is the attenuation coefficient. From Maxwell's equations for the configuration plasma surrounded by vacuum (plasma torch) we obtain the dispersion equation describing the wave propagation. The dispersion equation is local because of the plasma axial inhomogenity. Its solutions are presented as phase diagrams (dependence of plasma frequency on the propagation coefficient) and attenuation diagrams (dependence of plasma frequency on the attenuation coefficient). Analyzing the solutions of the local dispersion equation (phase and attenuation diagrams) one can obtain lots of information about the electromagnetic wave propagation along the plasma and its ability to sustain the discharge at given conditions.

The self-consistent link between the electrodynamic and kinetic parts of the model is based on energy balance: the wave power absorbed by the electrons (calculated in the electrodynamic part) is expended in collisions with heavy particles for ionization, excitation, and other elementary processes (calculated in the kinetic part).

3. Results and discussion

The self-consistent axial model is applied to surface-wave-sustained argon plasma columns of different radii R (from 0.05 cm to 1 cm).

The axial distribution along the plasma torch with various radii of the mean electron energy is presented in Fig. 3. It is about 1.5–2 eV close to the wave launcher and is increasing at the end of the torch to about 3.5 eV. With plasma radius increasing the mean electron energy increases.

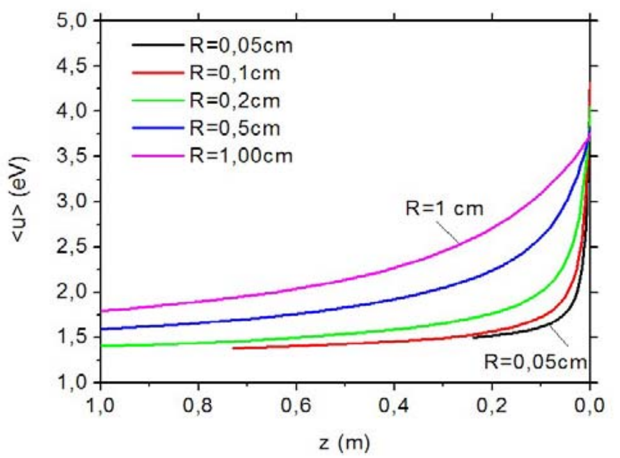

Fig. 3. The mean electron energy axial profiles at various plasma radii

Similar behaviour can be found in the axial distribution of the electron–neutral collision frequency (Fig. 4) and the mean power for electron–ion pair production (Fig. 5). They also change along the torch increasing from the launcher to the plasma end and with the plasma radius.

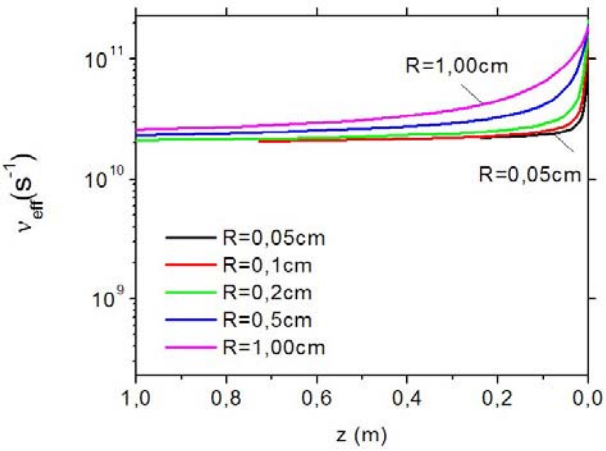

Fig. 4. The electron–neutral collision frequency axial profiles at various plasma radii

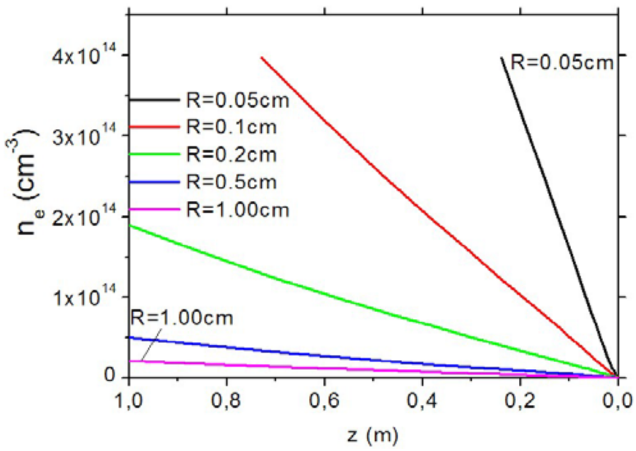

Fig. 6. Plasma density axial profiles at various plasma radii

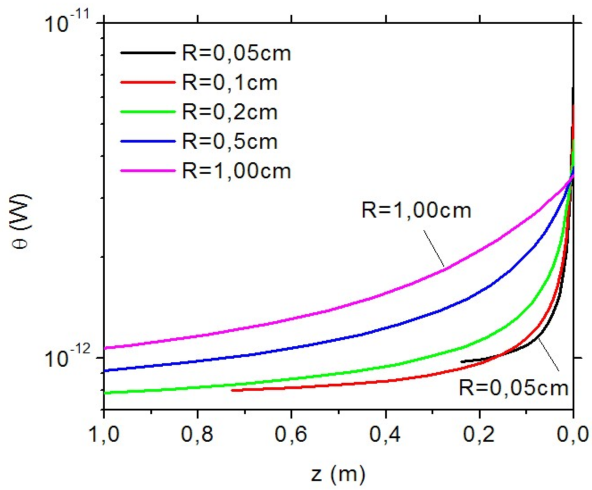

Fig. 5. The power for electron–ion pair production axial profiles at various plasma radii

The behaviour of the plasma density axial profiles is just the opposite: the plasma density decreases from the wave launcher to the end of the torch and with the plasma radius (Fig. 6). At smaller radius the torch is shorter but with higher plasma density gradient. Actually, at such conditions we have microplasma with high plasma density and low electron temperature (defined as 2/3 of the mean electron energy).

4. Conclusion

The axial variation of plasma characteristics shows that for plasma torch sustained by travelling electromagnetic wave it is necessary to solve all equations at each position along the plasma column. All plasma characteristics have a strong dependence on the plasma radius.

Even at atmospheric pressure the EEDF is non-Maxwellian and it is changing along the plasma column.

This investigation shows that the modelling cannot be simplified by using a single value for key parameters like the electron–neutral collision frequency for momentum transfer ν_{eff} and the mean power for sustaining the electron–ion pair in the discharge θ. They have to be calculated in each point along the inhomogeneous plasma column.

5. Acknowledgments

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